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CHARACTERIZATION OF THE MECHANISMS PRODUCING BENDING MOMENTS IN POLYSILICON MICRO-CANTILEVER BEAMS BY INTERFEROMETRIC DEFLECTION MEASUREMENTS

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ABSTRACT

Polysilicon micro-cantilever beams and doubly-supported beams are fabricated and conditioned with phosphorus doping and high temperature anneal cycles to assess the effects of process history and geometry on polysilicon microstructure rigidity. Using a Linnik interferometer, deflection trends for series of beams are measured and compared for several process conditions. Two bending moments can induce beam deflection: the first due to the beam boundary support, and the second due to stress nonuniformity through the beam thickness. A comparison of polysilicon microstructure deflection behavior for doping and annealing conditions is presented and discussed.

INTRODUCTION

Surface-micromachining techniques have been employed to create a polysilicon microbridge vapor sensor and planar pressure transducer [1, 2]. Successful fabrication of these suspended microstructures critically depends on the ability to reliably and routinely deposit low pressure chemically vapor deposited (LPCVD) polysilicon films with known physical properties. In particular, the stressed condition of polysilicon films presents design limitations for the development of microstructures since film warpage determines the maximum free standing lateral dimensions of a suspended microstructure. Guckel used measurements of doubly-supported polysilicon beam deflection as a function of geometry to determine the residual strain of thin polysilicon films for a given film condition [3]. Howe compared the buckling length of polysilicon cantilever beams with different process conditions to characterize the stress of thin polysilicon films for these conditions [4]. Together, these techniques provide an in situ method for determining the combined effects of geometry and process history on the structural rigidity of suspended microstructures. This study utilizes measurement of both cantilever beam deflection and doubly-supported beam buckling to distinguish the origins of polysilicon film warpage for differing film conditions and geometry.

EXPERIMENTAL

The polysilicon micro-beams are fabricated using surface-micromachining techniques on <100> oriented, 4-inch, 2 Ω-cm, n-type silicon wafers. A 0.8 μm-thick, undoped, sacrificial oxide layer is deposited on the wafers using a 400° C LPCVD cycle with a deposition rate of 125 Å/min. Trenches are patterned and dry-etched in the oxide layer to expose the underlying silicon surface. Pure silane is reacted at 250 mT and 625° C to deposit LPCVD polysilicon films ranging in thickness from 0.25 - 1 μm with a deposition rate of 100 Å/min. Half of the samples are phosphorus doped during a 60 minute diffusion cycle at 925° C using a $POCl_3$ liquid diffusion source. The samples are then patterned and anisotropically dry-etched using CCl_4 to form cantilevers and doubly-supported beams. Half of the doped and undoped samples then are annealed in a nitrogen ambient at 1150° C for 20 minutes. The suspended structures are released using 48 wt% hydrofluoric acid to undercut the oxide spacer layer, and are dried under a chemical hood after being rinsed in deionized water and methanol. Some undoped structures are released using the vapors of evaporating 48 wt% hydrofluoric acid to remove the oxide film, requiring no final rinse or dry cycle [5].

Once dried, the beams are inspected for vertical deflections using a Linnik interferometer attached to the 100X objective of an optical microscope. When viewed through the interferometric objective, cantilever and doubly-supported beams like those of Figs. 1 and 2 display interference fringes generated by the passage of coherent light through the interferometer's lenses onto the suspended structures. As shown in Figs. 3 and 4, the interference fringe patterns follow the deflection profile of the structures. Spacing of the straight fringes in the field regions of Figs. 3 and 4 corresponds to the half-wavelength of the coherent light used - the 5240 Å sodium yellow line. This distance provides coordinates for calibrating the vertical beam deflections. A measure of the angle, θ, defined by the curvature of the fringe profile between a beam boundary support and the edge of a cantilever or the center of a doubly-supported beam determines the vertical beam deflection, δ, as

$$\frac{\delta}{L} = \mathrm{Tan}\theta \frac{\lambda}{2D}, \qquad (1)$$

where L is the suspension length, λ is the illuminating light's wavelength, and D is the separation between two undeflected fringes. With the ability to resolve 1/10 of a fringe spacing, accuracy of the vertical deflection measurements is 250 Å.

Deflections are measured for series of cantilever beams and doubly-supported beams for each of four polysilicon film conditions: undoped, unannealed and annealed; and doped, unannealed and annealed. The cantilever beams range in length from 10 - 70 μm with 2 μm increments in length, and are 15 μm-wide, while the bridges range from 10 - 100 μm in length with 5 μm length increments, and are 15 μm-wide. All cantilever samples are 0.5 μm-thick, while for each polysilicon condition, doubly-supported beams are fabricated of 0.25, 0.5, 0.75, and 1 μm-thick films. Samples used for the two annealed conditions are inspected before and after the annealing cycles; comparison of the pre-anneal and post-anneal structural profiles indicates that no pre-release deflection of any structures occurs due to "softening" of the oxide spacer layer during the anneal cycle.

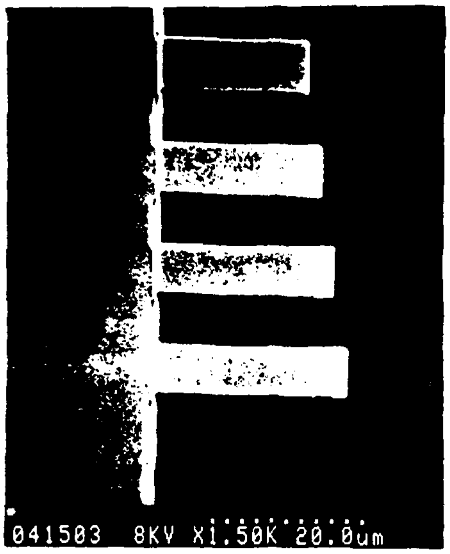

Figure 1. Released polysilicon cantilever beams

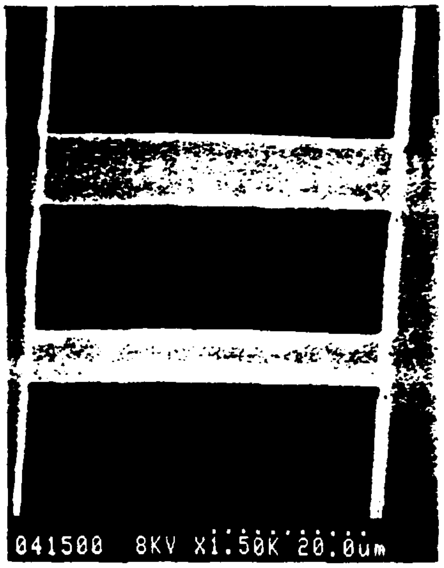

Figure 2. Released polysilicon doubly-supported beams

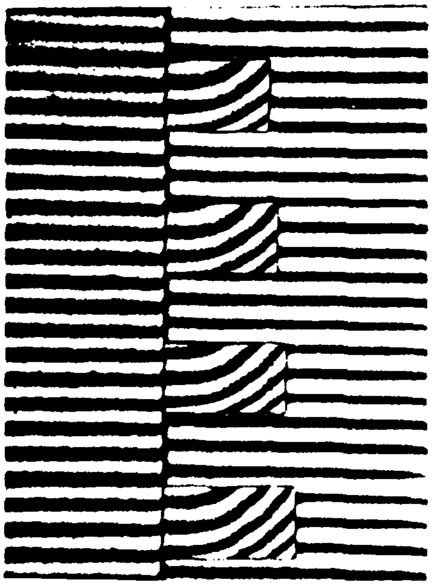

Figure 3. Interference pattern of beams in Fig. 1

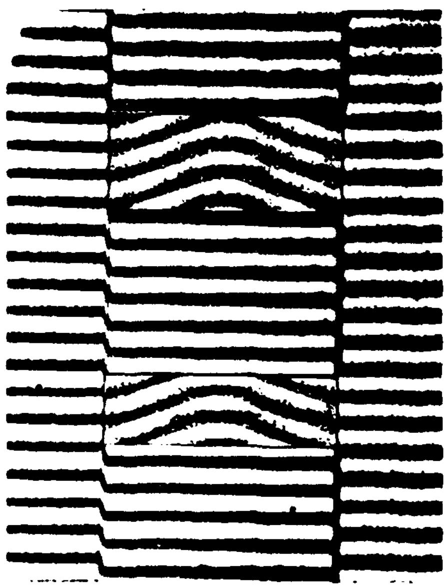

Figure 4. Interference pattern of beams in Fig. 2

RESULTS

Singly Supported Beams

Deflection trends for the undoped cantilever samples, etched with liquid HF (LHF) or vapor HF (VHF), are shown in Fig. 5 as a function of length. For the cantilevers released with the liquid etchant, deflections are upward for short beams, but the beams deflect downward and become stuck to the substrate at all lengths greater than 30 - 32 μm. This large deflection and sticking may be due to surface tension effects from the liquid etch and rinse baths and surface conditions of the suspended structures and the substrate. Deflections of the VHF-released samples match those of the LHF-released samples for short beam lengths, but never change direction to bend downward and touch the substrate. This indicates that the downward deflections of longer LHF-released beams are not caused by built-in bending moments but rather by the etch technique, so that deflections of beams less than 30 μm-long adequately characterize deflection trends due to built-in bending moments. Deflections of VHF-released beams longer than 50 μm are also upward, but too large to accurately measure with the interferometer.

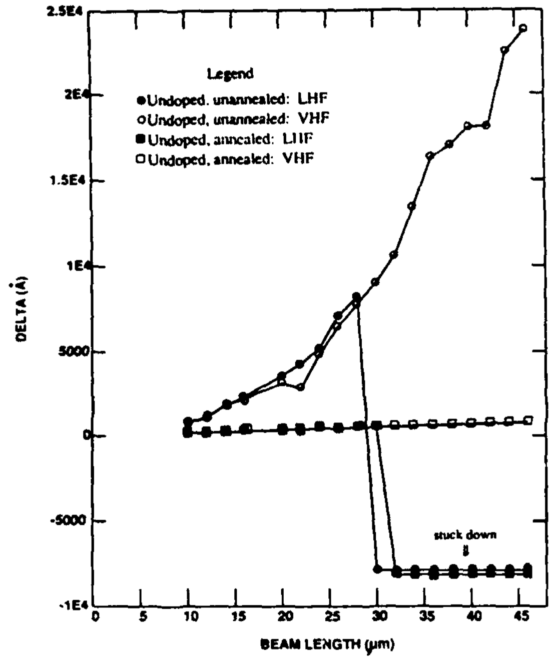

Figure 5. Deflection, δ, as a function of length for undoped cantilever beams etched with LHF or VHF

Two bending moments can induce cantilever deflection, as shown in Fig. 6. The first is due to the clamped step-up boundary, and causes a deflection linearly dependent on the cantilever length, L. The second is due to stress nonuniformity through the beam thickness, and causes a deflection that depends quadratically on L. Since the effects are additive [6], the combined effect of both moments is of the form

$$\delta \propto K_1L + K_2L^2. \qquad (2)$$

Thus, a plot of δ/L versus L should be a straight line, with an intercept at K_1 reflecting the boundary bending moment, and a slope K_2 reflecting the stress nonuniformity.

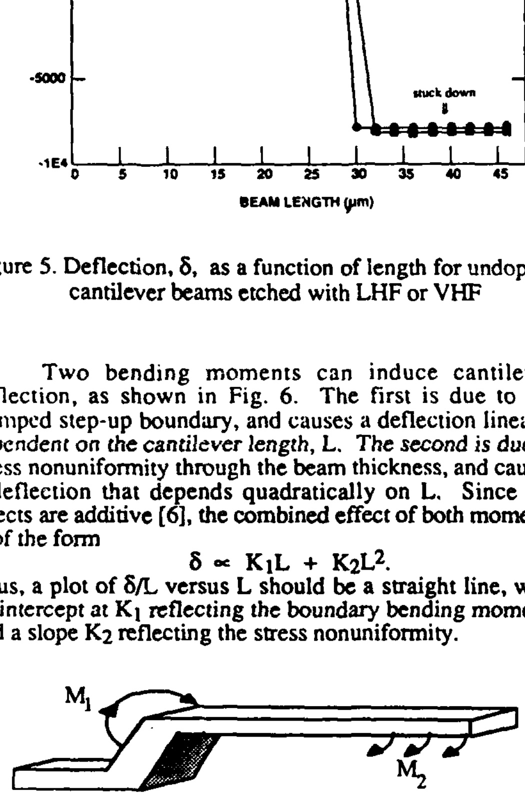

Figure 6. Built-in bending moments of cantilever beams

Figure 7 illustrates the dependence of δ/L on L, the cantilever length, for the four polysilicon beam film conditions, all released with LHF. Trends for the undoped cantilevers, unannealed and annealed, with either positive or zero slope, respectively, indicate upward beam deflection, while the negatively sloped trends of the two doped cantilever conditions indicate deflections downward. The y-axis intercept of the four trends represents K_1 in the model above, and the slope of each line indicates K_2, confirming that the observed deflection behavior agrees with the model.

Deflections of the undoped, unannealed samples indicate a large boundary moment and stress nonuniformity, while the undoped, but annealed samples exhibit a much smaller boundary moment and negligible stress nonuniformity. This demonstrates that the 1150° C annealing cycle effectively reduces both the bending moment due to the step-up boundary and the intrinsic stress nonuniformity through the film thickness. Deflection data

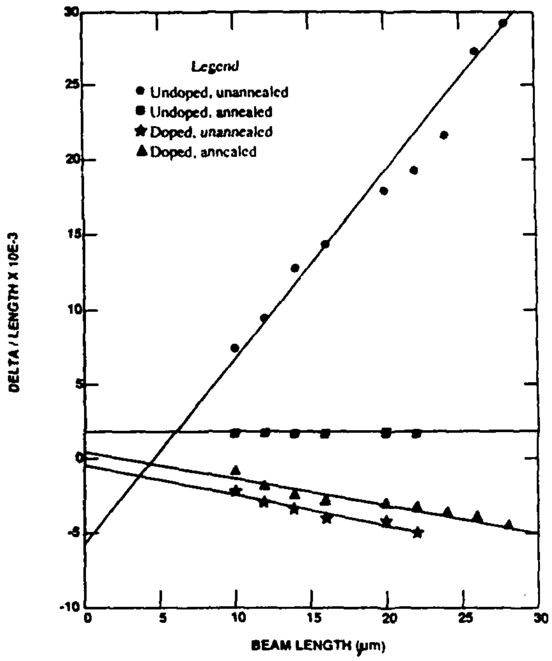

Figure 7. δ/L as a function of length, L, for polysilicon cantilever beams with four process conditions: undoped, unannealed and annealed; and doped, unannealed and annealed

from samples for both doped conditions exhibit identical slopes, characteristic of a stress nonuniformity due to the doping profile through the films, and similar boundary bending moments. While all undoped beams deflect upward, the doped beams deflect downward, indicating that doped and undoped polysilicon films are in opposing states of stress nonuniformity. The similarity of the unannealed and annealed, doped beam deflections suggests that the grain structure of $POCl_3$-doped films is in a stable state of equilibrium after the doping cycle; the annealing cycle does not effectively alter this state.

Doubly-Supported Beams

Buckling lengths for the four doubly-supported beam conditions are shown in Fig. 8 as a function of polysilicon film thickness. At lengths less than the buckling length, L_c, the beams deflect upward, while at lengths greater than L_c the beams deflect downward. For the undoped beams, those conditioned with an anneal cycle exhibit a longer buckling length than those without the cycle, demonstrating that the anneal cycle has produced a more structurally rigid beam. L_c is constant for doped beams, regardless of their annealing condition, suggesting, like the cantilever deflections, that $POCl_3$-doped polysilicon films are in a stable equilibrium state. The increase in buckling lengths for thin beams beyond that predicted by the thicker beams may be explained by a simple model that accounts for compliance of the step-up beam supports. This model will be reported separately.

If compliance of the beam support is ignored, a good approximation for the residual strain level, ε_p, of the 1 μm-thick beams at the buckling length is estimated by Euler buckling theory [6] for each process condition as

$$\varepsilon_p = \frac{\pi^2 t_p^2}{3 L_c^2}, \qquad (3)$$

where t_p is the polysilicon film thickness, and L_c is the beam buckling length for each of the polysilicon process conditions. Based on Eq. (3), undoped, unannealed films exhibit the highest residual strain, 1.27×10^{-3}, while doped and annealed films exhibit 0.41×10^{-3}, the least residual strain. These values agree well with those previously

reported by Guckel [3], to indicate that high temperature doping and annealing cycles significantly reduce the residual strain of intrinsic polysilicon films, producing longer unbuckled beams than intrinsic films.

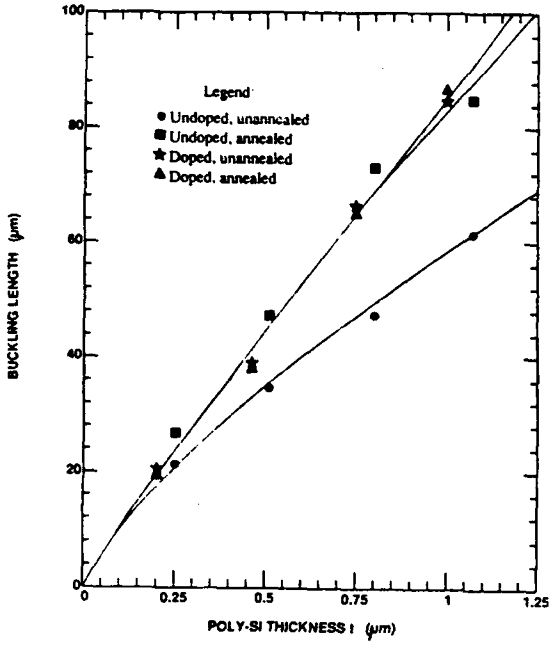

Figure 8. Buckling length as a function of film thickness for polysilicon doubly-supported beams with four process conditions: undoped, unannealed and annealed; and doped, unannealed and annealed

CONCLUSIONS

This study demonstrates that both end-effects and stress nonuniformity contribute to the deflections of suspended, surface-micromachined, polysilicon structures. High temperature annealing of the polysilicon film significantly decreases both the boundary bending moment and the intrinsic stress nonuniformity of the structures, thus increasing structural rigidity. Doping of the films also decreases these bending moments, but introduces an opposing stress nonuniformity possibly due to the doping profile through the film thickness, inducing further beam deflection. Calculation of the residual strain of doubly-supported beams at their buckling length demonstrates that the residual strain of intrinsic polysilicon is significantly reduced by high temperature phosphorus-doping and annealing cycles, providing the ability to fabricate larger suspended polysilicon microstructures.

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